SPE

Society of Petroleum Engineers

SPE 14503

Technically Recoverable Devonian Shale Gas in Ohio, West Virginia, and Kentucky

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ABSTRACT

Large volumes of natural gas may be technically recoverable from the Devonian shales of Kentucky, Ohio, and West Virginia. The technically recoverable gas from the Huron, Rhinestreet, Cleveland, and Marcellus intervals is estimated to range from 26 Tcf to 82 Tcf, depending on the success of new gas extraction technologies and practices. The total estimated in-place Devonian shale gas of this tri-state area is 394 Tcf. While much of the resource is in the Huron shale interval, significant portions are located in other thinner, yet organically rich, shale units that have experienced less development to date. This study represents the most current appraisal of Appalachian Devonian shale gas potential, and serves as an update of the 1980 National Petroleum Council work for this tri-state area.

INTRODUCTION

Devonian shales constitute one of the largest worldwide concentrations of organic carbon, and underlie a vast area of the Appalachian Basin in the Eastern U.S. However, technological challenges of efficiently recovering and economically producing gas from Devonian shales are yet to be solved. Full development of this resource has been greatly impeded by limited data and understanding of the gas production mechanisms in the organic shales.

This resource study relied heavily on new analytical capability and data. The versatile fractured reservoir simulator SUGAR (Simulator for Unconventional GAs Resources) was used to model the unique features of the shale, such as dual porosity, fracture flow, and permeability anisotropy. In addition the resource study assembled a large, long-term gas production file from 772 Devonian shale gas wells, used in calibrating the reservoir simulator.

The overall effort benefited from major studies that have been completed on the Devonian gas shales throughout the basin. Included are geological and geochemical assessments of the Devonian shales by the Mound Facility, Cliffs Minerals and various state geological surveys that provided valuable information on the fracture system, stratigraphic sequence, and gas content of the shales. Additionally, the resource study drew heavily from the results of field research, such as the Offset Well Test Program (OWTP) in Meigs County, Ohio, that identified the net productive interval and permeability anisotropy; the drilling of a deviated well that measured natural fracture spacing; and, the drilling of a series of Eastern Gas Shales Project core wells that established basic data on shale porosity, permeability, and organic carbon content.

PURPOSE

This study estimates the in-place and technically recoverable gas from the Devonian shales of Ohio, West Virginia, and Kentucky. For this, the study used a methodology specifically developed for analyzing the key technical issues of unconventional gas resources, including:

- How to characterize the major production mechanisms that govern the flow of gas in the Devonian shales?
- How to use secondary geologic/reservoir measures to define areas with good gas potential?
- How to select the most appropriate well stimulation techniques for the various geologic settings? and
- How to reliably simulate, through reservoir models, the gas flow rates and ultimate gas recovery?

The intended audience for the study includes persons interested in further understanding and appraising the variables that control Devonian shale gas production and are responsible for selecting appropriate well patterns, spacing, and stimulation techniques. The study examines the gas potential in broad regional, multi-county settings and, thus, does not represent findings for any specific lease area or well location in the state.

METHODOLOGY

The methodology for this study involves integration of geological data, reservoir properties, and historical gas production with reservoir simulation. The six major steps are:

1. Assembly of Geological and Reservoir Data on the Producing Devonian Shale Intervals. Here, the key studies and data sources were:

- Stratigraphic and paleontologic studies by the U.S. Geological Survey and State Geological Surveys;[1,2]
- Geophysical and goechemical studies by Cliffs Minerals, Mound Facility, and the U.S. DOE Morgantown Energy Technology Center;[3,4] and
- Data from key EGSP core wells.

2. Collection and Review of a Database on Historical Gas Production. A large compilation of Devonian shale gas production records for the three states was assembled from state sources, private company records, and the GRI database. After a review of over 3,600 wells, a gas production database with identifiable productive intervals, pressures, days on line, and annual flow rates was compiled for 772 individual Devonian shale wells. Records available by county are shown on Figures 1, 2, & 3 & Table 1.

3. Modeling and History Matching of Production Data, Productive Interval, and the Natural Fracture System. An advanced three-dimensional version (G3DFR) of the dual porosity reservoir simulator (SUGAR) was used to history match production data and back-calculate the remaining unknown reservoir parameters of fracture permeability and net productive interval, as well as ensure overall consistency of the input data. Special emphasis was placed on establishing the directional components of fracture permeability to reflect anisotropy, and on modeling the expected angle of intersection between induced and natural fractures to estimate whether the induced fracture would cross or terminate in the natural fracture system.[5]

4. Delineation of Stimulation Cases. Four well stimulation techniques were evaluated for their applicability to Devonian shales:

- Borehole Shooting (x_f = 1.8 feet): historically, borehole shooting has been the most often used technique in the Devonian shales;
- Radial Stimulation (x_f = 30 feet): small-scale radial stimulation potentially attainable with emerging technological improvements in high energy gas fracturing;
- Small Vertical Fracture (x_f = 150 feet): limited penetration vertical fractures are attainable, but not yet fully controllable or predictable with current technology; and
- Large Vertical Fracture (x_f = 600 feet): large-scale hydraulic fractures are potentially attainable for the shales with significant advances in fracture fluids, proppants, and stimulation technology.

5. Modeling of Stimulation Cases. Each of the stimulation cases requires an x-y grid-block layout in the G3DFR simulator to accommodate the radial or vertical fracture design (as shown in Figure 4). The fracture geometry for the four-wing radial stimulation assumes that the bottom-hole well pressure extends to the outer radius of the stimulation. For vertical fractures, the two fracture wings are assumed to have infinite conductivity along the full length of each wing. The calculated bottom-hole pressure boundary conditions are a function of estimated line pressure and well depth.[6]

6. Regional Appraisals of Gas In-Place and Potential Recovery. Devonian age shales were grouped into distinct geological settings within states because of the considerable geologic diversity within each state, as shown in Figures 1-3, and a distinct approach was used for the evaluation of in-place and potential gas recovery for each setting. Each Geological Setting was then divided into individual areas. The multi-county areas were determined by horizontal stress and natural fracture distribution, with 40-year cumulative gas production serving as a validation. Availability of reservoir and production data allowed estimates for a majority of the shale areas:

- In Ohio, there are six areas comprising one geological setting covering the eastern half of the state. The dominant intervals are the Middle and Lower Huron units of the Ohio shale (Figure 1).
- In West Virginia, three geological settings were established. Setting I, with six areas in the southern and western part of the state, is comprised of thick, radioactive Huron and Rhinestreet shale units. The deeper interbedded silts and sands of north central West Virginia form Setting II, and the deep Marcellus interval towards the eastern outcrop forms Setting III.

No estimates of gas recovery were possible for Setting III due to a lack of gas production data (Figure 2).

- In Kentucky, three geological settings were established. Setting I, with four areas along the eastern border of the state, is comprised of organically rich Huron, Cleveland, and Rhinestreet shales. The shales thin westward toward the outcrop in Setting II where estimates have been made based on the depth of the shale target. In Setting III the shallow depths and lack of gas production data precludes an estimate of recoverable gas (Figure 3).

GEOLOGICAL SETTINGS FOR DEVONIAN SHALE

To accurately simulate the Devonian shales of the Appalachian Basin an understanding of the structural and stratigraphic nature of the reservoir is necessary. The target interval from state-to-state changes in depth, gas content, thickness and permeability, all of which ultimately affects production. A stratigraphy column shown in Figure 5 represents the depositional history for most of the study area.

OHIO. Devonian shales occur in eastern Ohio in an area covering 25,000 square miles in 49 counties. The five principal radioactive zones of the shales thicken from 400 feet in central Ohio to more than 4,000 feet along the eastern border. The organically rich intervals in ascending order are the Marcellus, Rhinestreet, Lower and Upper Huron, and the Cleveland members. They overlie the Onondaga limestone and underlie the Berea sandstone. The Huron shale member (Upper Devonian), the basal member of the Ohio shale, is the most widespread of the Devonian shale sequences, ranging from an outcrop by the Cincinnati Arch to 350 feet of thickness at the eastern state border. The shales dip southeastward from the western outcrop in Cleveland County to 1,500 feet below sea level in southern Ohio in Gallia and Meigs Counties.

WEST VIRGINIA. The producing shales in southwestern and western West Virginia exhibit thick radioactive intervals of Huron and Rhinestreet that dominate production. The Big Sandy area of Lincoln, Mingo, and Wayne Counties has been the historical focus for much of the Devonian shale development in the state. Eastward, towards the north central portion of the state, the shales thin and are replaced by a sequence of Upper Devonian age interbedded sands, such as the Gordon, Balltown, Benson, and Riley. Underlying these shales and sands is the organically rich, deep Marcellus shale, which has had very little development to date.

KENTUCKY. The southeastern part of the state is comprised of the Big Sandy gas field and its extensions that cover over 3,000 square miles in Knott, Floyd, Martin, and Pike Counties. Gas production is from the thick, radioactive Huron and Cleveland shales of Upper Devonian age. Below these intervals is the deeper Rhinestreet shale. The Huron and Cleveland shales show increasing radioactivity westward, toward the outcrop, where the shales thin and converge into one undifferentiated zone. The Rhinestreet shale thins out entirely before the outcrop, and the other shale sequences in this area thin to less than 50 feet.

RESERVOIR DATA USED IN SIMULATION

Twelve key reservoir parameters are required to properly model gas flow and recovery for Devonian shales. The assembled geologic and reservoir data were divided into two categories and are shown in Table 2. Those reservoir properties that were found not to vary widely across the state were fixed at constant values for the entire state. For reservoir properties that were found to vary, individual data values were collected on a county-wide basis and extrapolated into counties where data were unobtainable.

CONSTANT RESERVOIR PARAMETERS

Drainage Area. A 160-acre spacing between wells was used in Ohio for simulations based on traditional practices. In West Virginia and Kentucky, an 80-acre spacing was used based on current trends.

Matrix Properties. Although a certain amount of variation in matrix properties was found, nominal values of 1% were used for shale matrix porosity and 5×10^{-6} md for matrix permeability. These values were based on measurements from the DOE/Offset Well Test Program and are supported by values from other EGSP core wells.

Fracture Porosity. The OWTP in Meigs County, Ohio, provided a value of 0.09% for fracture porosity. For lack of other data and because long-term production in the shale is essentially independent of fracture porosity, this value was used as a constant throughout the study area.

VARIABLE RESERVOIR PARAMETERS

Rock and Line Pressure. Initial rock (reservoir) pressure and producing line pressure were collected from company well records and well completion records to develop rock pressure isopach maps for the states.

Gas Content. Gas content contour maps, prepared from work by Mound, were used to estimate the volume of adsorbed and free matrix gas in each county, by shale interval.[4]

Fracture Spacing. The natural fracture spacing was determined by examining the number of joints per foot of shale interval, based on data in the Cliffs study.[3]

Fracture Permeability. Natural fracture system permeability versus depth was estimated for each study area using analysis developed by Terra Tek, Inc. and presented by Horton.[7]

Productive Thickness. The gross radioactive thickness of the shales was determined using work by the U. S. Geological Survey or by the various state surveys.

Permeability Anisotropy. For each partitioned area, the relative intensity of primary and secondary natural fractures from core wells was expressed as a ratio of permeability in the two horizontal directions, x and y.

HISTORY MATCHING

Long-term gas production data were used for the history match to determine the product of fracture permeability and net productive thickness. Representative wells were identified for those counties where sufficient production data were available to characterize the resource in a statistically meaningful way. In selecting representative wells, the database was screened to identify wells: (1) that were individually metered; (2) that had production from shale members distinguishable from other, non-shale producing horizons; (3) that included high, average, and low producers; and, (4) had at least five years of production data.

The history matches of long-term production for sample counties in each state are shown on Figure 6. Using the reservoir properties known for the representative counties, the G3DFR Model was employed to determine fracture permeability and the "net productive shale thickness" that matched the initial gas flow rate as well as matched long-term gas production.[7]

GAS IN-PLACE

The total Devonian shale gas resource in West Virginia, Ohio, and Kentucky is large, estimated at 394 Tcf. The gas is contained in a number of different black shale intervals, but predominantly exists in the Huron shale, as shown in Table 3. The three thick, rich black shale intervals (Huron, Rhinestreet, and Marcellus) contribute 360 Tcf while the leaner, thinner, and areally more limited shales (Java, Cleveland, Sonyea, and Genessee) contribute only 34 Tcf.

The gas in-place is contained in three sources:

- Free fracture gas is that gas filling the major fractures and joint systems;
- Free matrix gas is that gas which fills small microfractures and other microporous structures of the shale matrix; and
- Sorbed matrix gas is that gas absorbed or adsorbed by the organic matter in the shales.

The analysis show that the major portion of the gas in-place is sorbed matrix gas in all areas of the basin, as shown in the table below.

GAS IN-PLACE BY GAS SOURCE FOR TARGET INTERVALS

State	GAS IN-PLACE (% of Total, By Source) Free Fracture %	Free Matrix %	Sorbed Matrix %
Ohio	1	14	85
West Virginia	2	26	72
Kentucky	2	18	80

TECHNICALLY RECOVERABLE GAS

Technically recoverable gas from the Devonian shales is estimated at 26 Tcf using traditional stimulation technology in the currently being drilled areas. With advanced stimulation and the development of new shale areas, the potential could reach 83 Tcf. Due to the geology of Kentucky and West Virginia and the varying availability of data throughout the state, recoverable gas is calculated at different levels of detail, i.e., Geological Settings I, II, and III. In Geological Setting I, where a number of geologic studies have been completed, sufficient data exists to further subdivide the setting into analytical areas or plays. Technically recoverable gas is then calculated for each area as shown in Tables 4, 5 and 6. Areas designated as Geological Setting II have relatively good geologic data but generally contain only limited gas production data with which to verify the results of the simulation, thus gas recovery from these settings would be considered more speculative. Very limited geologic data and no gas production data are available for areas designated as Geological Setting III, thereby precluding estimates for recoverable gas for this setting.

OHIO. The analysis shows that the gas flow rates and ultimate recovery per well vary widely in Ohio, from relatively high gas production in the south to low production rates in the shallow, northern area along Lake Erie. The total recoverable gas in the state is estimated to range from 6.2 Tcf with borehole shooting to 15.2 Tcf with advanced stimulation (massive hydraulic fracturing).

In the southern portion of Ohio, in Lawrence and Gallia Counties, high gas recovery is due to favorable reservoir properties, such as high pressure, good net thickness and close fracture spacing (5-10 feet). Per well recoveries for borehole shooting are 386 MMcf with traditional technology and increase to 1,080 MMcf with large vertical fracturing (shown in Figure 7). As drilling progresses northward, despite the high adsorbed gas content, the production estimates decline due to low rock pressures. Estimates per well in the north central counties, Wayne and Stark Counties, range from 79 MMcf (borehole shooting) to 320 MMcf (large vertical fracturing). Gas production in northern Ohio is limited by low rock pressures in the shallow shales despite good gas contents and shale thicknesses.

WEST VIRGINIA. The total recoverable Devonian shale gas from West Virginia is estimated to range from 11.1 Tcf to 44.2 Tcf, depending on the completion and stimulation technology employed. Of this, 11 to 18 Tcf are recoverable from the better defined western portion of the state where the gas production is from the Huron and Rhinestreet members. In the traditional producing area of the Big Sandy field, Logan and Mingo Counties, favorable reservoir properties such as high permeability, thick net pay, limited anisotropy and close fracture spacing (5-10 feet) lead to high gas recoveries per well; 446 MMcf in 40 years with borehole shooting (shown in Figure 8). Large vertical fracturing adds little to ultimate recovery; however, it dramatically increases production in the initial years. For example, first year gas production rates increase from 67 Mcf/day (borehole shooting) to 510 Mcf/day (large vertical fracturing).

As drilling progresses northward, the estimates of recovery decrease towards the northern edge of the producing area comprised of Pleasants, Ritchie, and Wood Counties. Higher rock pressures, moderate net thicknesses and low natural fracture permeability combine to give per well recoveries of 218 MMcf (borehole shooting) and 355 MMcf (large vertical fracturing). First year gas production rates range from 30 Mcf/D to 155 Mcf/D, depending on the stimulation treatment selected.

Up to an additional 26 Tcf appear recoverable from the deeper, speculative Marcellus member in the north central counties of Setting II. In this area the natural fracture system of the deep Marcellus shale is tight (0.004 md) and poorly developed (25-foot spacing), thus large-scale stimulation or other approaches, such as a deviated well, may be required to unlock the full gas potential.

KENTUCKY. Technically recoverable gas from the Devonian shales of Kentucky is estimated at 9.4 Tcf using traditional borehole shooting in the currently drilled areas of the state. With advanced stimulation (600-foot fractures) and the development of new shale areas, the potential could reach 23.2 Tcf.

Part of the traditional producing area of the Big Sandy Field lies in eastern Kentucky and has produced natural gas from Devonian shale since the 1880s. Thus, remaining drillable area in this region has declined over time. For instance, in Martin and Floyd Counties, due to the extensive development in the last century (over 1,200 Devonian shale wells in this two-county area alone), only 319 square miles of a potential 630 square miles is now considered as undeveloped. The gas in-place for the entire setting (traditional producing area) is estimated to be 19.5 Tcf. As expected in this area, comparatively high permeability, thick net pay, limited anisotropy, and a close fracture spacing of five feet lead to a good gas recovery per well (962 MMcf in 40 years with borehole shooting), although the recovery efficiency is moderate, at 43% of the gas in-place. Moving northward from the Big Sandy Field area towards Lawrence and Johnson Counties and westward to Leslie and Perry Counties, per well production estimates range from 305 MMcf to 592 MMcf depending on stimulation (shown in Figure 9). Recovery efficiencies range from 47% recovery of the gas in-place with borehole shooting to 79% recovery with advanced technology.

The speculative areas of Geological Setting II in east-central Kentucky offer 2.6 Tcf to 7.2 Tcf of recoverable gas. Recent production in this area has been limited to five counties: Harlan, Bell, Breathitt, Morgan, and Clay. Wells in these counties are usually hydraulically fractured, comingled completions with moderate initial flows. Many of these wells are currently shut-in due to a lack of demand or a pipeline connection. Gas production is limited in this area due to shallow deposition and low rock pressures.

COMPARISON OF LEWIN RESULTS WITH OTHER STUDIES

Two previous studies have addressed the topic of Devonian shale gas and serve as benchmarks for comparison. The United States Geological Survey, in 1982, estimated gas in-place for the Appalachian Basin to be 844 Tcf, with approximately 427 Tcf estimated for the three states of Ohio, West Virginia, and Kentucky, as shown in Table 7. In addition, the National Petroleum Council (NPC), in 1980, completed both a resource appraisal of gas in-place and an estimate of technically recoverable gas.[11] The NPC study estimated 1,102 Tcf of black shale gas in-place for the Appalachian Basin, with 455 Tcf gas in-place for the three states of Ohio, West Virginia, and Kentucky. This study utilized more recent sources for black shale areal distribution, thickness and gas content to establish a gas in-place for the three-state area of 394 Tcf. While there is some variation among the studies at the state level, particularly as to black shale thickness and gas content, the gas in-place estimates for the tri-state area are comparable.

The major difference, and potential contribution of the DOE/Lewin study, is in the estimate of recoverable gas. The NPC estimated recoverable gas in the states of Ohio, West Virginia, and Kentucky to be 17 Tcf using borehole shooting and increasing to 31 Tcf using advanced extraction methods, as shown in Table 7. The NPC study estimated gas recovery using a single variable black shale thickness by county and a standard gas production decline curve. The current (DOE/Lewin) study estimated recoverable gas to be 26 Tcf using borehole shooting and 82 Tcf using advanced extraction methods. The estimates of production potential from this study are based on the full range of reservoir variables that govern gas recovery, including pressure, permeability, anisotropy, fracture spacing, gas content, and shale thickness.

The primary reason for the difference in recoverable gas between DOE/Lewin and the NPC study is the full recognition of the diversity of the geological/tectonic features that define the Devonian age shales of the Appalachian Basin.

- The NPC study, using data primarily from the historically productive Big Sandy Field area, assumed that the remainder of the Appalachian Basin would emulate well performance in the Big Sandy area. This required that permeability of the natural fracture system, and gas contents be relatively similar across the basin with black shale thickness being the primary controlling variable.

- The DOE/Lewin study established that the Devonian shale deposition outside the Big Sandy area was considerably different -- tighter, at times richer and less fractured -- than found in the Big Sandy. Thus, fracture permeability, fracture intensity and anisotropy became the important controlling mechanisms for gas recovery.

The second difference between the DOE/Lewin and NPC studies, arising from the above perceptions as to the controlling mechanisms for gas recovery, is the expected performance of improved well completions and stimulations.

- The NPC study used an inverse correlation "model" that correlates the initial productivity of a well to its capacity for improvement by stimulation, as shown on Figure 10. Such a "model," to be valid, has to assume that the "good" wells with high initial flows (high C_1, values on Figure 10) are highly fractured (naturally) and highly permeable, thus, are not able to benefit from stimulation. Conversely, wells with low initial gas production (low C_1, values on Figure 10) could double gas flow (an improvement ratio of 2) after stimulation, presumably because of low permeability. (Note that the logic for distinguishing varying rates of unstimulated gas flow was originally based on shale thickness only, and if this logic were carried over to the stimulation "model," it would lead to a vertical line or the same improvement ratio across all values of initial gas flow. Thus, there is a basic logical inconsistency in the NPC study.)

- The DOE/Lewin study used the SUGAR reservoir simulator to fully model the effects of fracturing and stimulation on gas recovery. In so doing it found that its results for the Big Sandy area -- represented by Lincoln County, West Virginia, on Figure 10 -- were essentially comparable to those of the NPC. However, in the geological settings outside the Big Sandy, where gas recovery is constrained by permeability and the nature of the natural fracture system, this study established that well stimulation would have considerably more beneficial effects than postulated by the NPC.

  - For example, for Logan County, West Virginia, DOE/Lewin established that larger scale well stimulation (well propped fracture half-lengths of 600 feet) would increase gas recovery by nearly three fold (improvement ratio of 2.7) as opposed to only 50% (improvement ratio of 1.5) as "modeled" by the NPC. Similar, results are seen for Lawrence County, Ohio, another perspective Devonian shale area outside the Big Sandy Field.

Other much smaller reasons for the difference between DOE/Lewin and the NPC are the length of the well life (40 vs. 30 years), the amount of potentially drillable area, the use of rectangular rather than square well spacing, and more optimum well spacing.

SUMMARY OF FINDINGS

Four major findings emerged from the assessment of the Devonian gas shales of the Appalachian Basin:

- Devonian Shale Gas In-Place is Estimated at 394 Tcf for the Organically Rich Black Shale Intervals of Ohio, West Virginia, and Kentucky. Of the total gas in-place, the "target" areas and intervals appraised in detail by this study contain 155 Tcf. This implies a large amount of gas potential is locked in speculative areas and intervals that are not yet being targeted for development.

- A Substantial Portion, 26 to 82 Tcf, of Natural Gas, Appears to be Recoverable from the Devonian Shales in Ohio, West Virginia, and Kentucky, Depending on the Completion and Stimulation Technologies Employed and the Shale Sequences That are Developed. Of this, 26 to 49 Tcf are recoverable from the traditional producing areas, depending on well stimulation. An additional 33 Tcf may be recoverable from the extension areas of the Devonian shale gas play with advanced stimulation. With the addition of speculative Devonian shale horizons in traditional areas, such as the Marcellus in West Virginia, advances in effective fracture lengths to 1,000 feet or the introduction of deviated wells, and extension of drilling beyond the "target" areas, the recoverable gas could be even greater.

- A Variety of Improved Production Strategies are required for Efficiently Recovering the Gas In-Place. The Big Sandy area, the historically developed area of the basin, has adequate natural fracture permeability (0.1 md) and fracture intensity (five-foot spacing) that allow acceptable gas recovery efficiencies to be obtained with small-scale stimulation. As drilling progresses into the tighter and less densely fractured areas of the Devonian shales, advanced field development, completion, and stimulation technologies will be essential. Here, closer well spacings, rectangular pattern layouts, multiple interval completions, and progressively larger volume fracturing and proppant transport technologies will be required to obtain economic gas flow rates.

- Considerable Additional Geological, Geophysical, and Engineering Data are Required to Properly Define and Achieve the Gas Production Potential of the Devonian Shales in the Appalachian Basin. Beyond the conventional gas storage and production variables, numerous other mechanisms, such as fracture permeability and intensity, permeability anisotropy and adsorbed gas, govern the efficient recovery of natural gas from Devonian shales. While past work has provided some of this data, a significant amount of extrapolation and reliance on assumption has been required to establish the estimates in this study. In addition, major variations in well performance exist within the same area defying traditional reservoir analyses and vastly heightening the risk of Devonian shale gas development. Thus, the Devonian shales remain a fruitful topic for geological and engineering research.

ACKNOWLEDGEMENTS

The authors thank the U.S. Department of Energy, Morgantown Energy Technology Center for their sponsorship of this research.

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TABLE 1

NUMBER OF DEVONIAN SHALE GAS PRODUCTION RECORDS USED IN THE STUDY

STATE	COUNTY	WELLS WITH GAS PRODUCTION
OHIO	Licking	25
	Lawrence	33
	Medina	10
	Meigs	19
	Monroe	7
	Other	6
WEST VIRGINIA	Jackson	53
	Kanawha	23
	Lincoln	44
	Logan	23
	Mason	10
	Mingo	48
	Jackson	53
	Pleasants	16
	Putnam	34
	Ritchie	20
	Wayne	26
	Wood	13
	Other	30
KENTUCKY	Floyd	61
	Knott	69
	Lawrence	20
	Letcher	14
	Martin	59
	Pike	48
	Other	8
TOTAL		772

TABLE 2

REQUIRED RESERVOIR PARAMETERS FOR SIMULATION

A. CONSTANTS	REPRESENTATIVE VALUE OR RANGE	SOURCE
Drainage Area, A	80–160 Acres	Historical Production
Matrix Permeability, k_m	5×10^{-6} md	Core Analysis & Simulation
Matrix Porosity, ϕ_m	0.01	Offset Well Test: Core Analysis
Fracture Porosity, ϕ_f	0.0009	Offset Well Test
B. VARIABLES, BY AREA		
Gas Content, G_c	10–220 MCF/AF	Mound Report
Initial Pressure, P_i	65–1000 PSIA	Well Records
Line Pressure, P_l	25–100 PSIA	Estimated
Fracture Spacing, a	5–30 FEET	Cliffs Minerals Report Stress-Ratio Map
Gross Thickness h_t	135–440 FEET	USGS And State Surveys
C. MATCHING PARAMETERS		
Fracture Permeability, k_f	.02–4 md	Estimates from Laboratory Tests: Simulation
Productive Interval, h	10–380 FEET	Simulation

TABLE 3

DEVONIAN SHALE GAS IN-PLACE BY INTERVAL

SHALE INTERVAL	GEOLOGICAL SETTINGS I	II	III	TOTAL
OHIO				
Lower and Upper Huron*	114.7	–	–	114.7
Rhinestreet	37.6	–	–	37.6
Marcellus	17.1	–	–	17.1
Cleveland	8.0	–	–	8.0
TOTAL	177.4	–	–	177.4
WEST VIRGINIA				
Huron Shale*	18.7	0.1	–	18.8
Java	0.4	–	–	0.4
Rhinestreet*	22.4	4.4	–	26.8
Sonyea	2.9	1.4	–	4.3
Genessee	2.3	2.8	–	5.1
Marcellus*	12.9	43.5	23.2	79.6
TOTAL	59.6	52.2	23.2	135.0
KENTUCKY				
Cleveland*	5.9	5.5	1.7	13.1
Lower and Upper Huron*	24.8	26.6	4.5	55.9
Java/Olentangy	1.9	1.5	–	3.4
Rhinestreet*	7.6	1.6	–	9.2
TOTAL	40.2	35.2	6.2	81.6
THREE STATE TOTAL				394.0

* Target Interval Studied.

TABLE 4

IN-PLACE AND TECHNICALLY RECOVERABLE GAS FROM DEVONIAN SHALES OF OHIO

PARTITIONED AREA	TOTAL DRILLABLE AREA (SQ. MI.)	GAS IN PLACE (TCF)	TECHNICALLY RECOVERABLE GAS (TCF) IN 40 YEARS: BOREHOLE SHOOTING	SMALL RADIAL STIMULATION r'_w=30'	LARGE RADIAL STIMULATION r'_w=60'	SMALL VERTICAL FRACTURE x_f=150'	LARGE VERTICAL FRACTURE x_f=600'
I	543	4.1	0.84	1.16	1.41	1.58	2.35
II	3,577	12.4	2.95	4.06	4.64	4.67	6.21
III	2,869	4.4	1.46	1.98	2.25	2.33	3.04
IV	2,641	24.8	0.84	1.35	1.73	1.78	3.38
V	313	0.4	0.05	0.06	0.06	0.06	N.A.
VI	1,035	3.3	0.04	0.07	0.10	0.09	0.20
TOTAL	10,978	49.4	6.18	8.68	10.19	10.52	15.18

SOURCE: LEWIN AND ASSOCIATES, 1983.[8]

TABLE 5

IN-PLACE AND TECHNICALLY RECOVERABLE GAS FROM DEVONIAN SHALES OF WEST VIRGINIA

PARTITIONED AREA	TOTAL DRILLABLE AREA (sq. mi.)	TARGET GAS IN-PLACE (TCF)	TECHNICALLY RECOVERABLE GAS (IN 40 YEARS) (TCF): BORE-HOLE SHOOTING	RADIAL STIMULATION x_f = 30'	SMALL VERTICAL FRACTURE x_f = 150'	LARGE VERTICAL FRACTURE x_f = 600'
1. GEOLOGICAL SETTING I Huron and Rhinestreet Shale						
AREA I	189	0.7	0.5	0.5	0.5	0.5
AREA II	688	5.1	2.4	3.0	3.5	3.9
AREA III	1,480	6.9	2.8	4.2	4.7	5.4
AREA IV	623	2.2	1.6	1.7	1.8	1.8
AREA V	1,379	7.2	2.4	3.2	3.6	4.4
AREA VI	809	3.2	1.4	1.8	2.0	2.3
SUBTOTAL	5,168	25.3	11.1	14.4	16.1	18.3
2. GEOLOGICAL SETTING II Marcellus Shale	4,407	43.5	8.0	11.0	16.5	25.9
SUBTOTAL	9,575	68.8	19.1	25.4	32.6	44.2
3 GEOLOGICAL SETTING III Marcellus Shale	3,600	23.2	*	*	*	*
4. OTHER NON TARGET SHALE INTERVALS	**	43.0	*	*	*	*
TOTAL	13,175	135.0				

*Not Calculated
**Contained in above total drillable area.

Source: Lewin and Associates, Inc., 1984.[9]

TABLE 6

IN-PLACE AND TECHNICALLY RECOVERABLE GAS FROM DEVONIAN SHALES OF KENTUCKY

	TOTAL DRILLABLE AREA (sq. mi.)	TARGET GAS IN-PLACE (Tcf)	TECHNICALLY RECOVERABLE GAS (In 40 Years) (Tcf): BOREHOLE SHOOTING	RADIAL STIMULATION x_f = 30'	SMALL VERTICAL FRACTURE x_f = 150'	LARGE VERTICAL FRACTURE x_f = 600'
1. GEOLOGICAL SETTING I						
Area I	319	5.4	2.5	3.2	3.8	4.4
Area II	474	2.8	1.7	2.0	2.3	2.4
Area III	919	8.1	3.7	4.8	5.5	6.3
Area IV	615	3.2	1.5	2.0	2.4	2.9
Subtotal	2,327	19.5	9.4	12.0	14.0	16.0
2. GEOLOGICAL SETTING II	4,047	17.0	2.6	4.0	5.1	7.2
Subtotal	6,374	36.5	12.0	16.0	19.1	23.2
3. GEOLOGICAL SETTING III*	2,324	6.2	–	–	–	–
4. OTHER NON TARGET** SHALE INTERVALS	–	38.9	–	–	–	–
TOTAL	8,698	81.6	–	–	–	–

*Technically recoverable gas is not calculated for this area.
**Drillable area for non target shale intervals is included in Geological Settings I–III. technically recoverable gas is not calculated for more target shale intervals.

SOURCE. Lewin and Associates, Inc., 1985.[10]

TABLE 7

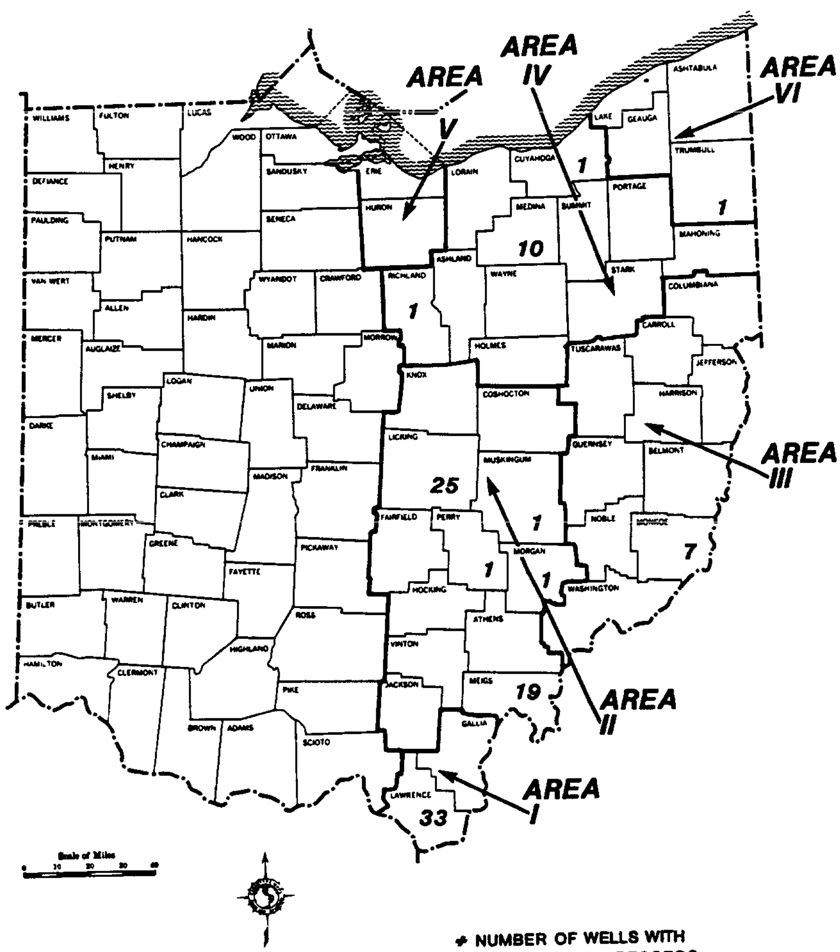
GAS IN-PLACE AND RECOVERABLE GAS ESTIMATES

STATE	GAS-IN-PLACE DOE/LEWIN Tcf	GAS-IN-PLACE NPC Tcf	USGS Tcf	RECOVERABLE GAS* DOE/LEWIN Tcf	RECOVERABLE GAS* NPC Tcf
OHIO	177	156	175	6-15	6-12
WEST VIRGINIA	135	246	190	11-44 **	6-11
KENTUCKY	82	53	62	9-23 **	5-8
3 STATE TOTAL	394	455	427	26-82	17-31
OTHER STATES	N/A	647	417	N/A	8-19
APPALACHIAN BASIN	N/A	1,102	844	N/A	25-50

* Traditional (Borehole Shooting) to advanced technology (600' Hydraulic Fracture)

FIGURE 1

OHIO STUDY AREA



* NUMBER OF WELLS WITH GAS PRODUCTION RECORDS

FIGURE 2

WEST VIRGINIA STUDY AREA WITH GEOLOGICAL SETTINGS

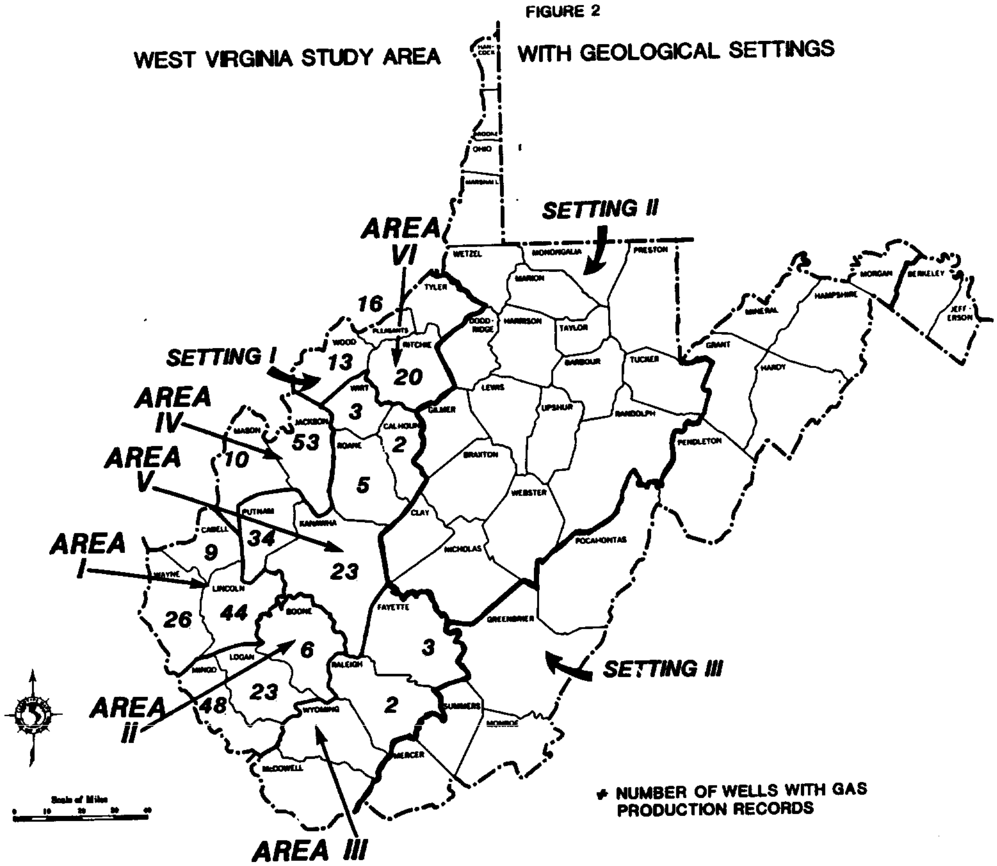


FIGURE 3

KENTUCKY STUDY AREA WITH SETTINGS

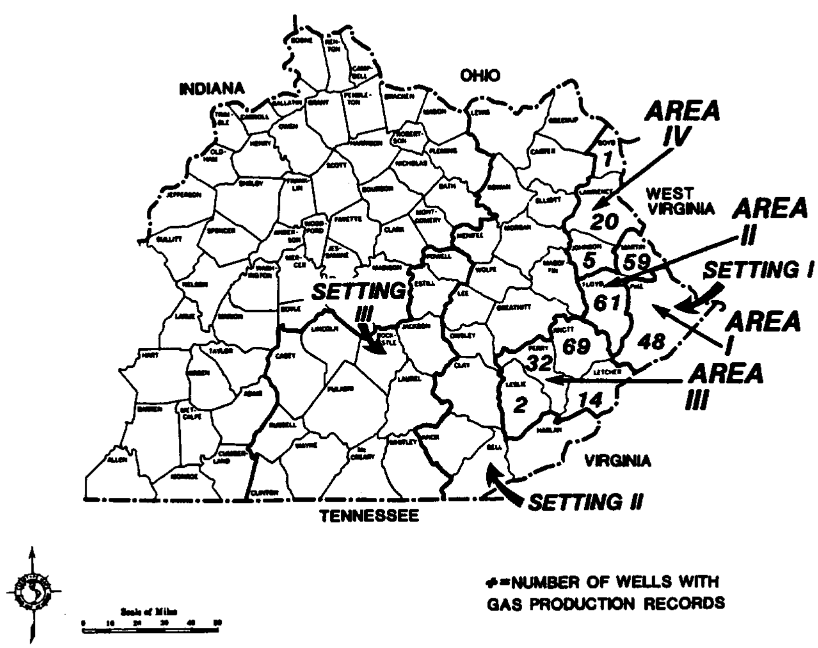
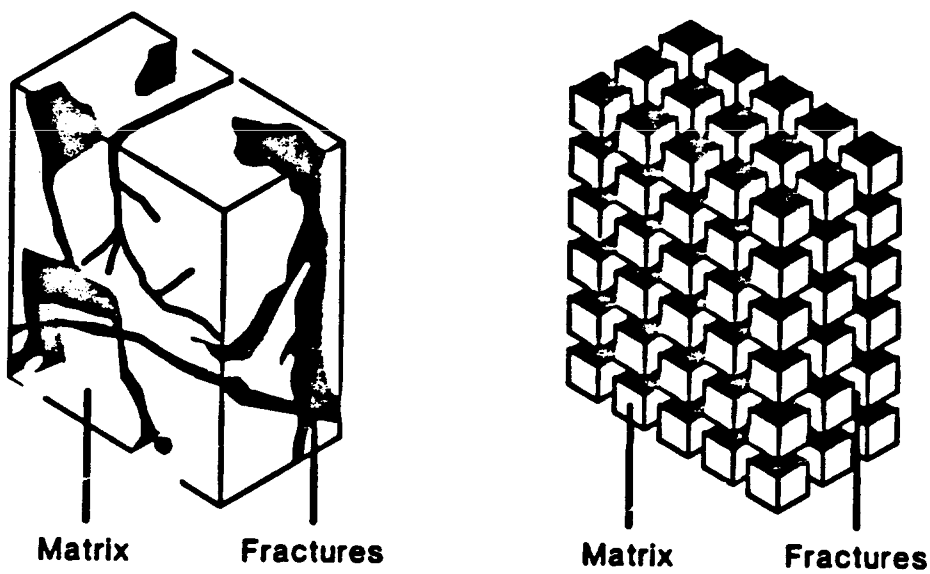


FIGURE 4

COMPARISON OF ACTUAL RESERVOIR VS. SIMULATED RESERVOIR

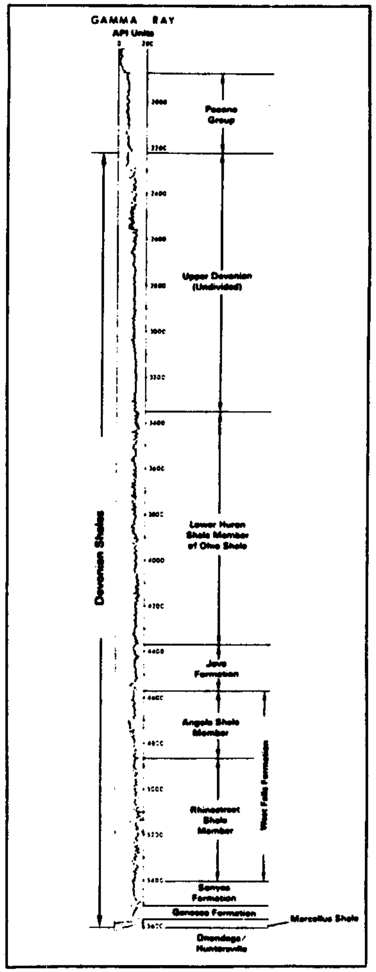


Actual Reservoir

Model Reservoir

FIGURE 5

TYPICAL DEVONIAN SHALE STRATIGRAPHY COLUMN



SOURCE: SWEENEY, HOHN, AND PATCHEN, WEST VIRGINIA GEOLOGICAL AND ECONOMIC SURVEY, 1985.

FIGURE 6

SAMPLE HISTORY MATCHES OF ACTUAL PRODUCTION DATA

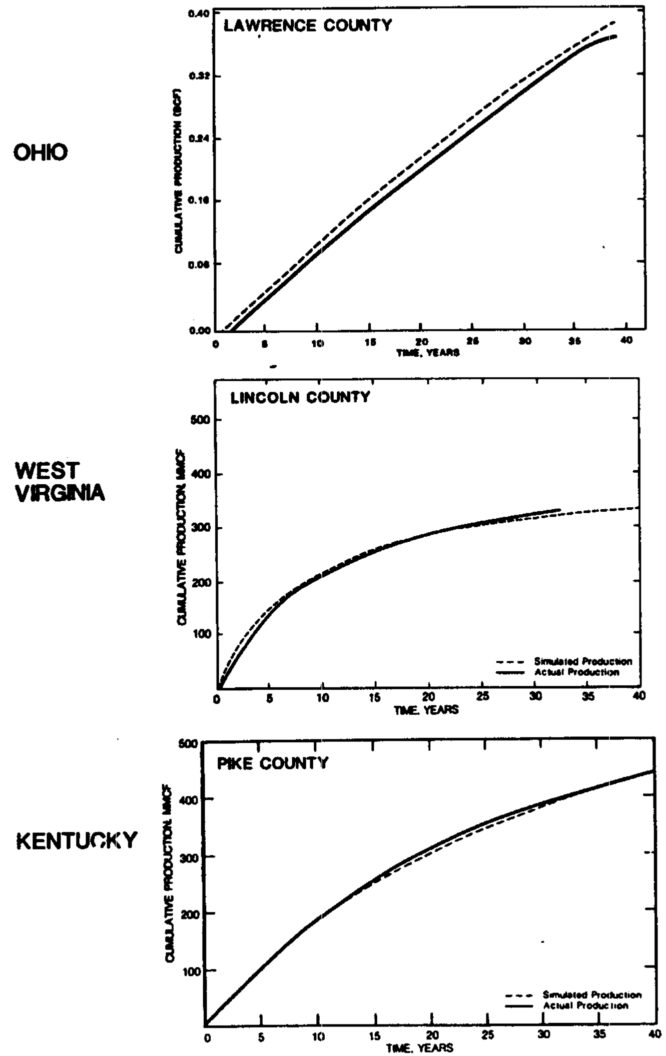
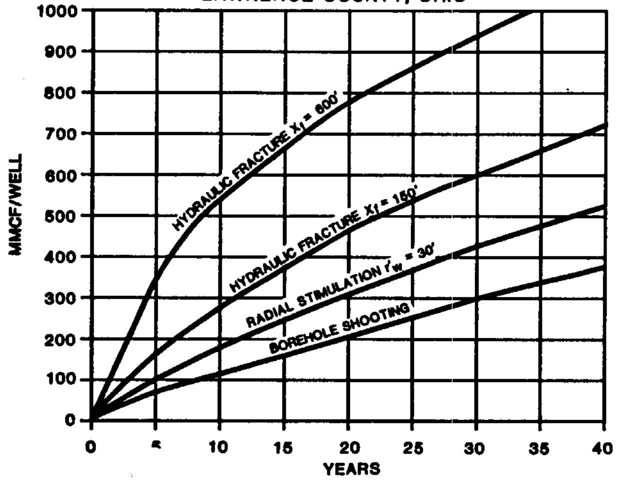


FIGURE 7

CUMULATIVE GAS RECOVERY

LAWRENCE COUNTY, OHIO



MEDINA COUNTY, OHIO

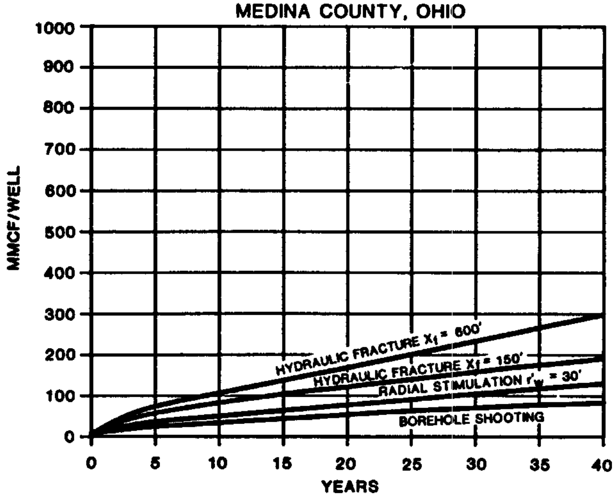
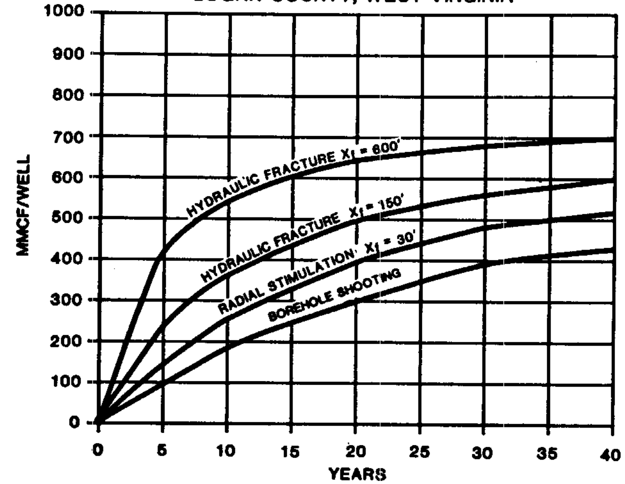


FIGURE 8

CUMULATIVE GAS RECOVERY

LOGAN COUNTY, WEST VIRGINIA



RITCHIE COUNTY, WEST VIRGINIA

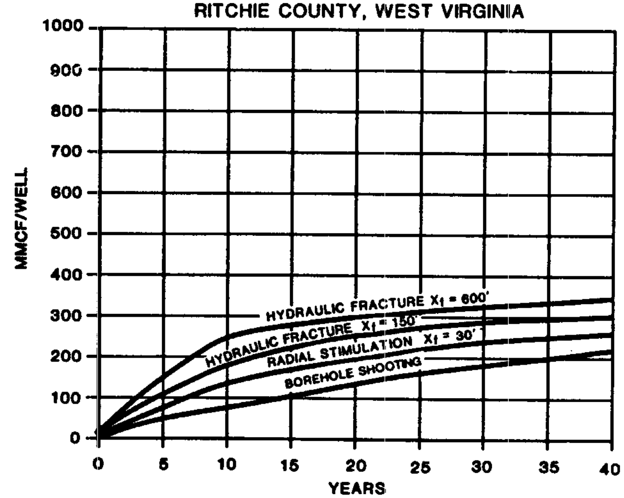


FIGURE 9

CUMULATIVE GAS RECOVERY

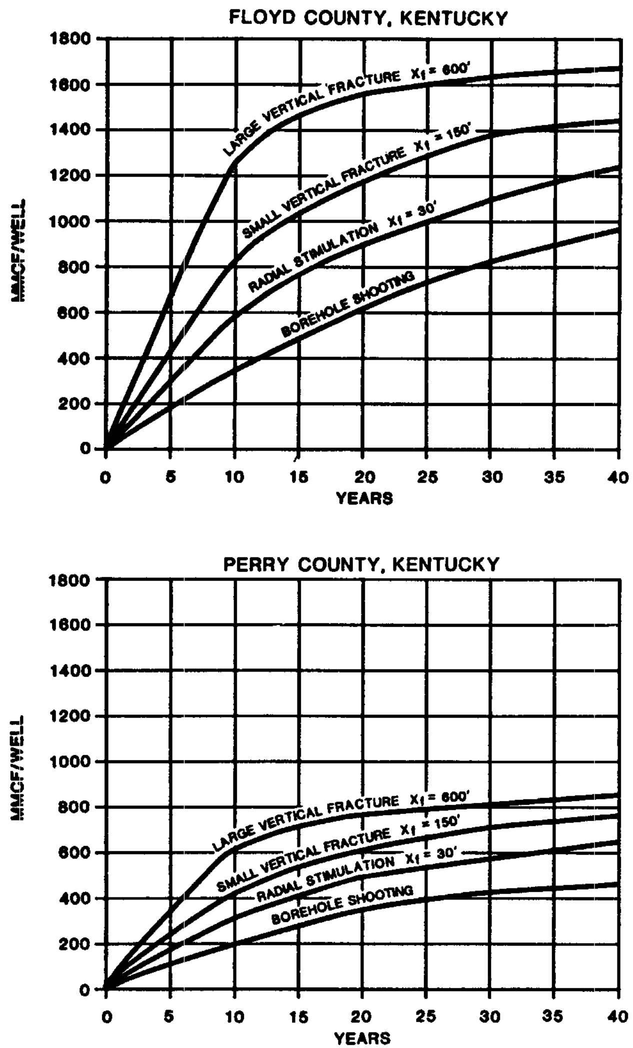
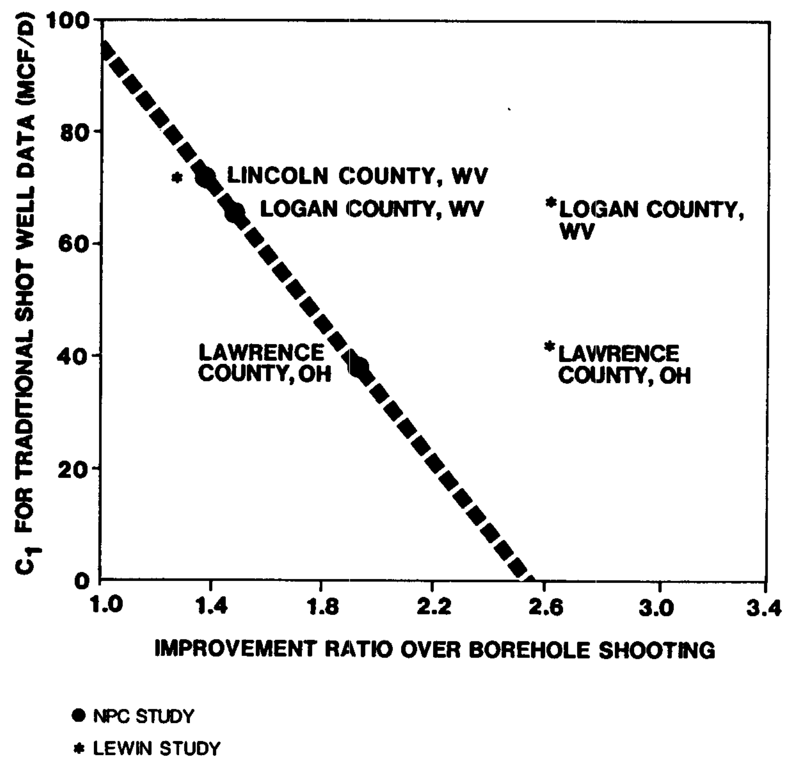


FIGURE 10

COMPARISON OF IMPROVEMENT RATIOS BETWEEN THE NPC AND LEWIN STUDY



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